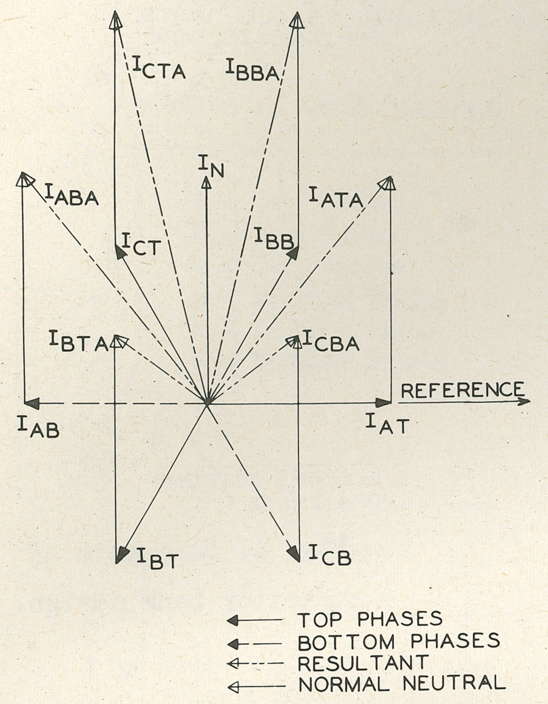

Fig. 6. Neutral current vector diagram before interchange.

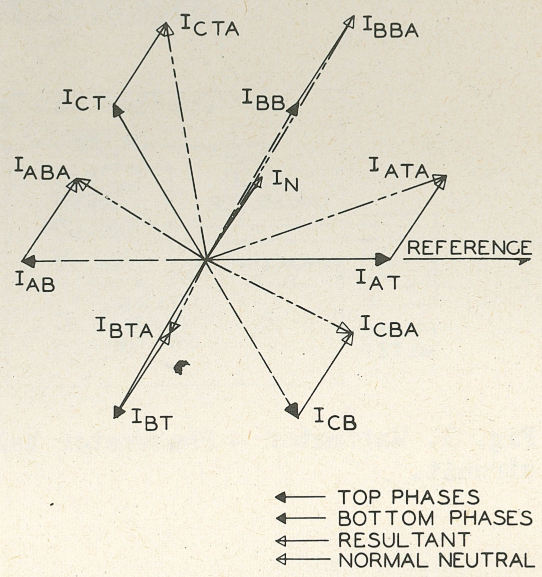

Fig. 7. Neutral current vector diagram after first interchange.

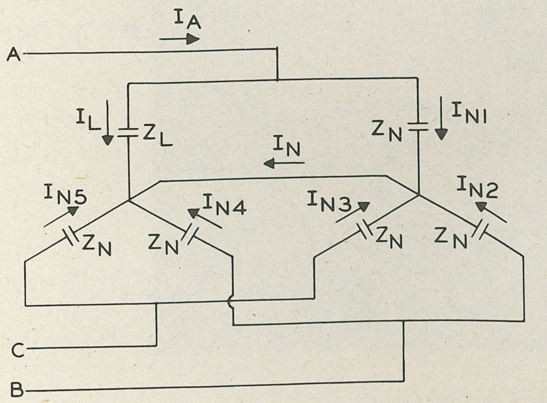

Fig. 8. Currents in double-wye connected capacitor bank.

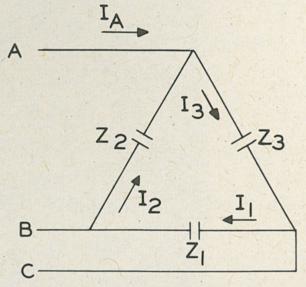

Fig. 9. Currents in equivalent delta connected capacitor bank.

Transactions Paper

(Reviewed and Accepted for Publication)

BALANCING DOUBLE-WYE HIGH VOLTAGE CAPACITOR BANKS

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A paper recommended by the AIEE Committee on Transmission and Distribution and approved by the Committee on Technical Operations for presentation at the AIEE Winter General Meeting, New York, N. Y., January 31-February 4, 1955. Manuscript submitted October 26, 1954; made available for printing December 8, 1954.

Price: 30¢ To Members
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American Institute of Electrical Engineers
33 West 39th Street, New York 18, N. Y.
Litho in USA

Paper No.
55-146

Discussion in Duplicate Due February 16, 1955.

BALANCING DOUBLE-WYE HIGH VOLTAGE CAPACITOR BANKS

O. R. Compton

Occasionally double-wye connected high voltage capacitor banks, using neutral current relaying, have sufficient residual current flowing in the neutral to cause improper relay operation thus endangering the capacitors. This paper summarizes the problem, establishes limits for the maximum allowable residual neutral current and presents methods for balancing the capacitor bank, if necessary, to reduce the residual neutral current to the allowable limit.

When a large, high voltage capacitor bank is composed of multiple series sections per phase and a sufficient number of parallel capacitor units per series section to meet the minimum bank size requirement, at least one capacitor unit may be removed from any series section without encountering voltages in excess of 110% of rated voltage on the remaining capacitors.[1] However, the loss of two or more units in any one series section can produce dangerous overvoltages within the section in which the units are lost.[1,2]

Protective relaying is often used to give indication and/or trip the bank when a sufficient number of units are lost within one series section to cause the voltage appearing across that series section to exceed 110% of rated voltage.[1] Since the majority of power capacitors used in the United States in high voltage banks are manufactured with a 0 to plus 15% tolerance, there may be sufficient inherent unbalance to cause the protective relay scheme to operate prematurely or not operate at all when needed, depending on the magnitude and phase angle of the residual current.[3]

In addition to unbalance caused by the variation in capacitance of individual units because of the 0 to plus 15% manufacturing tolerance, unbalance may also arise due to:

1. Units in upper tiers operating in higher ambients because of warm air rising from lower tiers.
2. Capacitors in top tier being subject to direct sunlight will operate at higher internal temperatures than units in lower tiers.
3. And, units in top tier will cast their shadows on lower tiers, thus causing units in lower tiers to operate at a relatively lower internal temperature.

Specifically this paper deals with double-wye connected banks using neutral current relaying since it is the most widely used system. Its popularity is the result of its low cost, when compared to other schemes which are also insensitive to external system conditions and yet extremely sensitive to unbalanced bank conditions. This was also the type relaying used on the Virginia Electric and Power Company's banks which were balanced by the method presented herein.

It is the purpose of this paper to present a basis for theoretically establishing a satisfactory maximum allowable neutral residual current and two methods of balancing double-wye connected capacitor banks when it is found the initial residual neutral current exceeds the maximum allowable limit.

DETERMINATION OF MAXIMUM ALLOWABLE RESIDUAL NEUTRAL CURRENT

Normally the neutral relay is set to pick up midway between the values of neutral currents theoretically obtained when the maximum permissible number of units and the maximum permissible number plus one unit in the same series section are lost. The maximum permissible number of units lost is defined as the maximum number that can be lost in one series section without the voltage across that section exceeding 110% of rated capacitor voltage.[1] This midway relay setting gives equal margin on either side to prevent premature relay operation when no more than the maximum permissible number are lost and to assure operation when one additional unit in the same series section is lost.

The maximum permissible number of units that may be removed from one series section may be determined by the curves of the equation shown in Fig. 1. The resulting neutral current may be determined for the loss of any number of parallel units in one series section by the curves of the equation in Fig. 2. The derivation of equations in Figs. 1 & 2 is shown in appendices I and II respectively.

The curves of Fig. 2 may also be used to establish the approximate neutral relay settings. For example, assume a double-wye connected bank made up of three series sections per phase and eight parallel units per section. From Fig. 1 it can be determined that the maximum permissible units that may be lost is one. When two units in the same series section are lost, the bank should be relayed off. Therefore, the neutral current relay should be set to pick up at a value of current equal to the loss of approximately one and one-half units or loss of (1.5/8) (100) = 18.75 units. Entering the curves on Fig. 2 at the loss of 18.75% units will indicate a relay setting of 1.8% of total bank current.

The relay setting in per cent of total bank current may be specifically determined by the use of the following equation:

$$I_R = \frac{1}{2}\left[\frac{150}{6N\left(\frac{M}{K+1} - 1\right)+5} + \frac{150}{6N\left(\frac{M}{K} - 1\right)+5}\right] \qquad (1)$$

MAXIMUM ALLOWABLE NORMAL RESIDUAL NEUTRAL CURRENT WITH ALL UNITS IN SERVICE

It can be readily seen that under normal conditions the maximum neutral residual current must be something less than one-half of the difference between the theoretical neutral currents obtained when the maximum permissible number of units and the maximum permissible number plus one unit are lost.

A realistic limitation of the maximum would be one-fourth of the difference in neutral currents when the maximum permissible number of units and the maximum permissible number plus one unit are lost. The maximum allowable residual current in per cent of total bank current may be determined by the following equation:

$$I_R = \frac{1}{4}\left[\frac{150}{6N\left(\frac{M}{K+1} - 1\right)+5} - \frac{150}{6N\left(\frac{M}{K} - 1\right)+5}\right] \qquad (2)$$

This value of maximum allowable residual current would provide ample margin against false tripping and at the same time avoid the trying task of obtaining a super fine degree of balance.

The residual neutral current component due to the difference in capacitance of units allowed by the 0 to plus 15% manufacturing tolerance will remain essentially constant for a given bank. However, the residual neutral current may vary to a slight degree because of the difference in internal operating temperatures because of the effect of upper tiers operating in higher ambients and being subjected to direct sunlight.

Variations in capacitance due to different internal operating temperature could be substantial since the capacitance of an askarel treated capacitor decreases approximately

1% for every 15-20°C. rise in internal operating temperature. Experience has shown that units in the top tier can easily operate with internal temperature of 5°C. to 10°C. above the internal temperature units in the bottom tier.

Fortunately most high voltage capacitor banks are so arranged that the effect of different internal operating temperatures is distributed throughout the bank, so that the approximate respective balance is maintained. However, there is ample margin to allow for some degree of changing unbalance due to different internal operating temperature when the value of maximum allowable residual current specified above is maintained.

FIELD BALANCING OF DOUBLE-WYE CONNECTED HIGH VOLTAGE BANKS

The following discussion will describe the general procedure incorporated to balance the No. 4 and No. 5 capacitor banks rated 24,750 KVAR, 108 KV, 3-phase, double-wye connected, at the Virginia Electric and Power Company's Peninsula Substation. Both banks are identical in design and are shown schematically in Fig. 4. A photograph of Bank No. 5 is shown in Fig. 5. Each bank is made up of standard 25 KVAR, 4160 volt, single-phase distribution capacitors with fifteen series sections per phase and eleven parallel units per series section.

The resulting voltage rise across a series section due to the loss of one capacitor within that section is 9% as determined from Fig. 1. Since the loss of two units in the same series section results in a voltage exceeding 110% of rated capacitor voltage, it is necessary to relay the bank off when more than one unit is lost in the same series section.

The theoretical neutral current flowing when one and two units are lost is 0.24 amps. and 0.51 amps. respectively. Therefore, the neutral relay is set to pick up at (1/2) (0.24 + 0.51) or 0.375 amperes. Likewise, the maximum allowable residual neutral current limit is established to be (1/4) (0.51 - 0.24) or approximately 0.07 amperes.

With the maximum allowable residual neutral current limit established at 0.07 amperes the resulting neutral currents would range between 0.24 + 0.07 and 0.51 ± 0.07 amperes when one and two units were lost respectively. The exact value of the resulting neutral currents when one or two units are lost would depend on the particular phase group in which the units were lost and the magnitude and phase angle of the residual neutral current.

Each bank was energized to determine the initial residual neutral current. It was found the initial residual currents were 0.295 amperes for Bank No. 4 and 0.265 amperes for Bank No. 5. It is obvious that these magnitudes of residual neutral current would cause false relay operation. For example, in Bank No. 4 the loss of one unit in any one of the six phase groups could cause a resulting neutral current of 0.24 ± 0.295 amperes. With the relay set at 0.37 amperes, the bank could be easily relayed off unnecessarily. Similarly, with two units lost the neutral current in Bank No. 4 could range between 0.51 + 0.295 amperes and this could result in two units being removed without encountering sufficient neutral current to pick up the relay and thus endangering the remaining units in the series section containing the lost units because of overvoltage operation.

Procedure

The following steps constitute the general procedure followed in balancing the No. 4 & No. 5 Banks at the Peninsula Substation:

1. Determine the magnitude of initial residual neutral current.

2. Determine phase angle of initial residual neutral current.

3. Determine the phase sections contributing to the initial residual neutral current and capacitance change necessary to reduce the residual neutral current to within the maximum allowable limits.

4. Interchange high and low capacitance units to accomplish the capacitance change dictated by step number 3.

1. Magnitude of Initial Residual Current

The magnitudes of the initial residual currents were determined by energizing each bank and measuring the neutral current on the secondary side of the one-to-one neutral current transformer. The initial residual neutral currents were 0.295 amperes and 0.265 amperes respectively for Banks No. 4 and No. 5.

2. Phase Angle of Initial Residual Current

Neutral current measurements were made on each bank with one capacitor out of one section of one phase group. This test was repeated six times to enable the phase angle of the initial residual neutral current to be determined by graphical analysis. It would, of course, have been possible to determine the phase angle with fewer measurements. For each test the bank was normal except one capacitor was removed from the series section nearest the neutral in a different phase group each time. The results of these tests are shown in Table I for Bank No. 4.

It was calculated that the phase group in which the one unit was removed would supply a 0.24 ampere neutral current in phase with the line current. Therefore, six vectors, each sixty electrical degrees apart and each with a magnitude of 0 .24 amperes were plotted, as in Fig. 6. The magnitude only was measured for each of the six conditions where one unit was removed, as above. This magnitude was the vectorial sum of the 0.24 ampere in-phase component plus the component produced by the capacitance unbalance (initial residual current) an unknown angle.

If a circle is drawn with a radius equal to the initial residual current, as found in Item I above, and centered at the head of a 0.24 ampere in-phase vector, that circle will be the locus of all possible total neutral currents when one unit is removed from that phase group. A second circle with a radius equal to the total neutral current with its center at the origin is drawn. This second circle will also be the locus of all possible total neutral currents. These two circles will intersect at two points; one of which is the locus of the initial neutral current vector.

For example, in Fig. 6, a circle with radius equal to I normal is drawn with the head of vector I_{AT} as the center. Then a second circle is drawn with the center at the origin and a radius equal to the total neutral current measured when one unit is removed from the A phase, Top group. These two circles will intersect at the head, of vector I_{ATA} and at a second point 180 electrical degrees (through the head of vector I_{AT}) from I_{ATA}. A line drawn from the head of vector I_{AT} to each of these intersecting points will be the two possible normal unbalance current vectors. These vectors are equal in magnitude and 180 electrical degrees apart in angle.

This procedure is repeated for another phase group and it becomes apparent which is the correct direction for the normal unbalance current vector.

The graphical analysis for determining the phase angle relationship of the initial residual or normal unbalance current is shown in Fig. 6 for Bank No. 4. This current was found to be 0.295 270° amperes.

An analysis of Table I will reveal that the loss of one unit from any section in B-Bottom phase, or C-Top phase of Bank No. 4 would have produced a breaker trip with a relay setting of 0.37 amperes. In the remaining phase groups, two or more capacitors would have to be removed from the same series section to produce a breaker trip.

3. Phase Groups Contributing to Unbalance

A study of vector diagram for Bank No. 4 shows that the neutral current was high on B-Bottom phase and C-Top phase when one capacitor was removed from these respective groups. The neutral current was equal in both A-Top and A-Bottom phase groups when one capacitor was removed from either of these groups.

It was assumed that B-Bottom phase and C-Top phase contributed equally to the initial neutral current. That is, 0.295 / 2 or 0.148 amperes was contributed by each of these phase groups. The phase angle between B-Bottom phase and C-Top phase is about 30° above and below the initial residual neutral current. Therefore the gross current component contributed by B-Bottom phase and C-Top phase equals (0.148/cos 30°) or 0.171 amperes.

If 0.24 ampere equals the theoretical neutral current produced by the loss of one unit, the 0.171 ampere component equals the current produced by the equivalent loss of 0.171/0.24 or 0.71 of a unit. This indicates a balance could be obtained by moving 0.71/2 or 0.35 of a unit from B-Top phase to B-Bottom phase and 0.35 of a unit from C-Bottom phase to C-top phase.

4. Calculation of Number of Units to Interchange

Each unit contains approximately 4.0 microfarads of capacitance, therefore, it was necessary to interchange (0.35) (4) or 1.40 microfarads between the B-phase groups and C-phase groups. To determine which units to interchange a capacitance bridge was used to measure the capacitance of units in the top and bottom tiers of phase B and C. Individual unit capacitance was taken of each individual unit starting with the series sections nearest the neutral. This procedure was continued until a sufficient number of high and low units were found to make a total transfer of 1.24 microfarads from B-Top phase to B-Bottom phase and from C-Bottom phase to C-Top phase respectively. In order to accomplish this change in capacitance, 20 units were interchanged in the B-phase and 18 units were interchanged in the C phase.

After the interchange was completed a check was made of the residual neutral current and it was found to be 0.13 amperes. Therefore, it was necessary to repeat the balancing procedure.

The results of tests taken to determine the phase angle of the residual current after the first interchange are shown in Table II, and Fig. 7 shows the graphical analysis for determining the new residual neutral current to be 0.13/182° amperes.

An analysis of Fig. 7 indicated an additional transfer of 0.84 microfarads was needed from B-Top phase to B-Bottom phase. The 0.84 microfarad change was accomplished by interchanging 12 additional units in the B phase.

The residual neutral current was checked after the second interchange and was found to be 0.046 amperes which is within the maximum allowable residual neutral current of 0.07 amperes.

The same procedure was used to balance Bank No. 5. The initial neutral residual current was 0.265 amperes. After interchanging 26 units in B phase and 18 units in C phase the residual neutral current was reduced to 0.098 amperes. A second interchange of 12 units was made in C phase which reduced the residual neutral current to 0.072 amperes which is considered satisfactory.

Substation Operating Procedure

It was first decided to lower the system voltage at the Peninsula Substation each time the banks were energized for a neutral current measurement test in order to offset the voltage rise caused by the capacitors. This required considerable time for system coordination before each test and as a result tests proceeded rather slowly the first day. Since it required only approximately three seconds to make each current measurement, it was decided by the System Operator that no voltage drop would be required before energizing the bank. The voltage reduction is more harmful than the three second voltage rise. After this change in procedure was made, neutral current measurement tests were conducted very rapidly.

When making capacitance measurements prior to selecting specific units to interchange, it was found that approximately 4 units would have to be measured for capacitance for every two units interchanged. One hundred units were measured in Bank No. 4 before selecting 50 to interchange; 112 units were measured in Bank No. 5 before selecting 56 units to interchange.

It required four days to attain the proper balance on both banks.

BALANCING WITH PHASE METER AND WATTMETER

Since the original balancing of the capacitor banks at Peninsula Substation, a simpler method of determining the phase angle of the neutral current has been developed. This method can utilize either a phasemeter to compare the phase angle of the neutral current with a reference potential, or a wattmeter for comparison of real power derived from the neutral current with each of six reference potentials. These methods use a circuit as illustrated in Figure 3.

This method utilizes the residual neutral current and one of six potentials as input quantities into a phasemeter and a wattmeter. See Fig. 3. The six potentials are sixty electrical degrees apart.

With these quantities, it is possible to determine the phase angle of the residual neutral current and then proceed with the balancing as disussed above.

The wattmeter may have an application in normal operation. It is the practice of the Operating Department to inspect the capacitor installation once a week. This inspection if for blown fuses and other discrepancies. Since there are almost 4000 capacitor unit fuses in the installation, the inspection is quite time consuming. A single-phase wattmeter might be installed on the control panel for each bank. A blown fuse would cause a rise in the residual neutral current of the bank which would be indicated on an ammeter on the control panel. If the inspector notes a rise in the residual neutral current, he would proceed to apply the different potentials to the wattmeter with a rotary switch. By noting the maximum wattmeter indication, he could determine which phase group has a blown fuse. The equipment for this installation would not be expensive.

CONCLUSIONS

The following conclusions are based on the characteristics and procedure for balancing high voltage, double-wye connected capacitor banks:

1. Double-wye connected high voltage banks may have sufficient initial residual current to cause improper operation of the neutral current relay used to prevent overvoltage operation of capacitor units when an excessive number of units are lost in one series section.

2. The normal residual neutral current with all units in service is the result of

    (a) Zero to 15% manufacturing tolerance of individual capacitor units,

    (b) Variation in capacitance of units due to different unit temperatures resulting from capacitors in top tiers operating at higher ambient temperatures than those in lower tiers because of warm air rising from below, direct sunlight and casting their shadows on lower tiers.

3. It may be found necessary to balance the bank by shifting individual capacitor units to reduce the residual neutral current to within an allowable limit to permit proper neutral relay operation. Maximum allowable residual current specified as 1/4 of the difference in neutral currents obtained when the maximum permissible number of units are lost and permissible number plus one additional unit.

4. Shifting units will counteract unbalance caused by zero to plus fifteen per cent manufacturing tolerance. Unbalance caused by item b in Conclusion No. 2 usually may be neglected providing bank is arranged so changes in capacitance due to different internal operating temperatures will be equally distributed throughout all six phases groups.

5. Double-wye connected capacitor banks may be easily balanced in the field by using the following procedure, when it is found that the initial residual neutral current exceeds the maximum allowable value specified in Conclusion No. 3:

    (a) Determine magnitude and phase angle of initial residual current.

    (b) Determine phase groups contributing to unbalance and calculate magnitude of capacitance change in the various phase groups necessary to reduce the initial residual current to near zero.

    (c) Balance bank by interchanging high and low capacitance units to achieve calculated capacitance change necessary to achieve proper balance.

6. Balancing in the field can be eliminated if proper consideration is given to the problem by the engineers designing the bank. By balancing the phase groups on paper and then adhering to a strict unit placement program during field erection there should be no problem of "tolerance unbalance."

7. A single phase wattmeter or a phase meter can be used to determine which phase group contains a blown fuse on a large bank.

The author wants to express his appreciation to Mr. P. E. Hendrickson for his assistance in the preparation of this paper. He also wishes to express his appreciation to Mr. J. A. Rawls, Mr. T. S. Martin, Mr. B. B. Brown and Mr. E. F. Eldred, all of Virginia Electric and Power Company for their encouragement and constructive criticism of this paper.

REFERENCES

1. Engineering Aspects of Large High-Voltage Banks - P. E. Hendrickson, N. R. Schultz- Distribution Magazine, Schenectady, New York, October 1953, Vol. 15 No. 4, Paper 20 - 23.

2. Report on the Operation and Maintenance of Shunt Capacitors - AIEE Technical Paper 49 - 252.

3. Standards For Shunt Capacitors - NEMA - Publication No. CA1-1959.

NOMENCLATURE

Z_e - Impedance of phase section in which one or more units in one series section has been lost.

Z_n - Impedance of normal phase sections.

M - Number parallel units per series section.

N - Number of series sections per phase section.

K - Number of units lost in one series section.

K_1 - Percent of units lost in one series section.

I_a - Total bank current to phase in which K units have been lost.

I_{a1}- Normal total bank current.

I_e - Current in phase section in which K units have been lost.

I_{n1}, I_{n2}, I_{n3}, I_{n4}, I_{n5} - Current in remaining phase sections.

E - Source line to neutral voltages.

E_{ab}, E_{bc}, E_{ca}, - Source phase-to-phase voltage.

e_f - Voltage across series with K units lost.

e_{n1}- Voltage across series section under normal conditions.

I_N- Neutral current.

$\%I_N$- Neutral current in percent of normal total bank current.

I_{aT}- Assumed neutral current resulting from one unit being removed from top section of A phase.

I_{aTA}- Actual neutral current when one unit is removed from top section of A phase.

I_N - Actual residual neutral current with all units in service.

APPENDIX I

DETERMINATION OF NEUTRAL CURRENT

The following equations can be written by inspection of Fig. 8:

$$I_{n1} + I_{n2} + I_{n3} - I_n = 0 \qquad (3)$$

$$I_1 + I_{n4} + I_{n5} + I_n = 0 \qquad (4)$$

$$I_{n2} = I_{n3} = I_{n4} = I_{n5} \qquad (5)$$

Solving equations (3), (4) & (5) for I_n

$$I_N = \frac{I_{n1} - I_1}{2} \qquad (6)$$

Neutral current in percent at normal total bank current is:

$$\% \; I = \left|\frac{I_N}{I_{a1}}\right| \text{ X } 100 \qquad (7)$$

Normal total bank current (when $Z_e = Z_n$) is:

$$I_{a1} = \frac{2E}{Z_n} \qquad (8)$$

Substituting equation (8) in equation (7):

$$\% \; I_n = \frac{Z_n \; I_N \; 100}{2E} \qquad (9)$$

By inspection of Fig. 8:

$$I_a = I_{n1} + I_1 \qquad (10)$$

$$I_1 = I_a \frac{Z_n}{Z_1 + Z_n} \qquad (11)$$

$$I_{n1} = I_a \frac{Z_1}{Z_1 + Z_n} \qquad (12)$$

Substituting equations (11) & (12) into equation (6)

$$I_N = I_a \frac{(Z_1 - Z_n)}{(Z_1 + Z_n)} \qquad (13)$$

To solve for I_a convert double-wye network (Fig. 8) to delta-network (Fig. 9).

$$Z_1 = Z_n + \frac{Z_n \; (Z_1 + Z_n)}{4Z_1} \qquad (14)$$

$$Z_2 = \frac{Z_n}{2} + \frac{2 \; Z_1 \; Z_n}{Z_1 + Z_n} \qquad (15)$$

$$Z_3 = \frac{Z_n}{2} + \frac{2 \; Z_1 \; Z_n}{Z_1 + Z_n} \qquad (16)$$

By inspection of Fig. 9:

$$I_a = I_3 - I_2 \qquad (17)$$

$$Ia = \frac{E_{ab}}{Z_3} - \frac{E_{ca}}{Z_2} \qquad (18)$$

From equations (15) & (16):

$$Z_2 = Z_3 \qquad (19)$$

Substitution equation (19) into equation (18)

$$I_a = \frac{1}{Z_2} (E_{ab} - E_{ca}) \qquad (20)$$

The following voltage equalities may be written:

$$E_{ab} = \sqrt{3E} \qquad (21)$$

$$E_{ca} = a\sqrt{3E} \qquad (22)$$

Substituting equations (21) & (22) into equation (20) & solving for I_a

$$I_a = \frac{3ja^2E}{Z2} \qquad (23)$$

Substituting equation (15) into equation (23)

$$I_a = \frac{3ja^2E}{\frac{Z_n}{2} + \frac{2Z_eZ_n}{Z_e + Z_n}} \qquad (24)$$

Substituting equation (24) into equation (13)

$$IN = \left(\frac{3ja^2E}{Z_eZ_n + Z_n^2 + 4Z_eZ_n}\right) (Z_e - Z_n) \qquad (25)$$

Substituting equation (25) into equation (9) & neglecting voltage & impedance angles

$$\%I_n = \frac{3}{2} \frac{(Z_e - Z_n)}{(5Z_e + Z_n)} \ (100) \qquad (26)$$

However:

$$Z_n = \frac{-jXcN}{M} \qquad (27)$$

$$Z_e = \frac{-jXc(N-1)}{M} + \frac{-jXc}{M-K} \qquad (28)$$

Substituting equation (27) & (28) into equation (22)

$$\%I_n = \frac{150}{6_n\left(\frac{M}{K} - 1\right)} + 5 \qquad (29)$$

Equation (27) in terms of % units lost is:

$$\%I_n = \frac{150}{6n\left(\frac{100}{K_1} - 1\right)} + 5 \qquad (30)$$

APPENDIX II

DETERMINATION OF RESULTING OVERVOLTAGE

$$e_K = \frac{I_e(-jXc)}{M-K} \qquad (31)$$

$$e_{nl} = \frac{I_{al}(-jXc)}{2M} \qquad (32)$$

$$\%e_f = \frac{e_K}{e_{nl}} \times 100 \qquad (33)$$

Substituting equations (31) & (32) into equation (33)

$$\%e_f = \frac{I_e}{I_{al}} \frac{(2M)}{(M-K)} \ 100 \qquad (34)$$

Substituting equations (8) & (25) into equation (34) & neglecting voltage & impedance angles:

$$\%e_f = \frac{6MZ_n}{(5Z_l + Z_n)\ (M-K)} \ 100 \qquad (35)$$

Substituting equations (27) & (28) into equation (35)

$$\%e_f = \frac{600\ MN}{6N(M-K)} + 5K \qquad (36)$$

Equation (36) in terms of % units lost is:

$$\%e_f = \frac{60000\ N}{6N(100 - K_1)} + 5K_1 \qquad (37)$$

TABLE I
NEUTRAL CURRENTS PRIOR TO FIRST INTERCHANGE
BANK NO. 4

Location of Unit Removed	Neutral Current (Amperes)
A - Top Phase	0.355
B - Top Phase	0.110
C - Top Phase	0.530
A - Bottom Phase	0.355
B - Bottom Phase	0.560
C - Bottom Phase	0.215

TABLE II
NEUTRAL CURRENTS AFTER FIRST INTERCHANGE
BANK NO. 4

Location of Unit Removed	Neutral Current (Amperes)
A - Top Phase	0.330
B - Top Phase	0.110
C - Top Phase	0.328
A - Bottom Phase	0.201
B - Bottom Phase	0.375
C - Bottom Phase	0.220

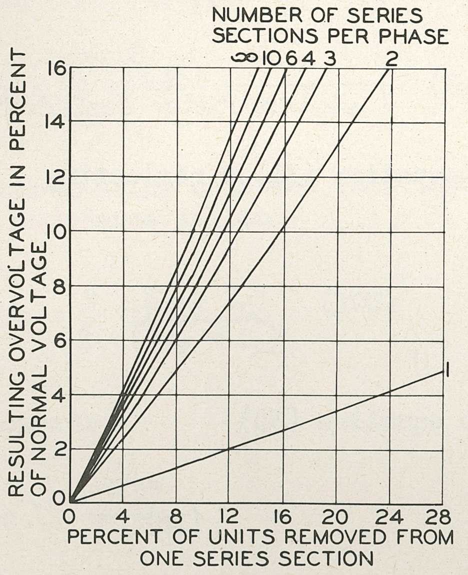


Fig. 1. Curve of overvoltage on remaining units in series section vs. percentage of units removed from that section.

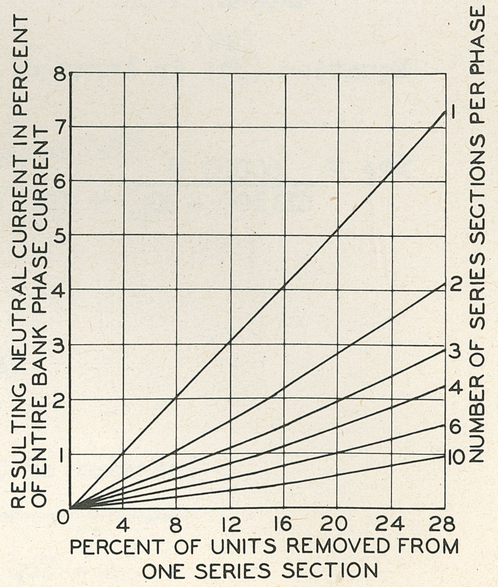


Fig. 2. Curve of neutral current vs. percentage of units removed from one series section.

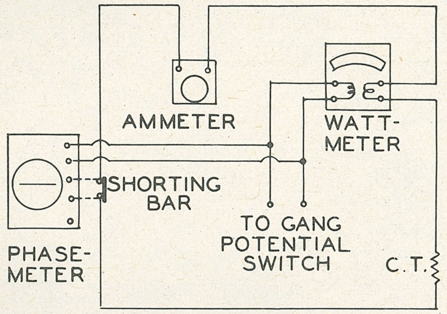


Fig. 3. Wattmeter - Phasemeter balancing circuit.

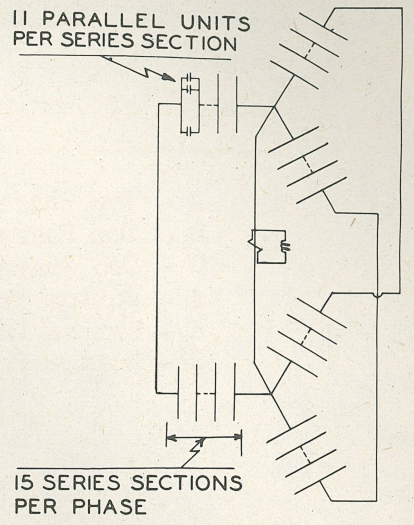
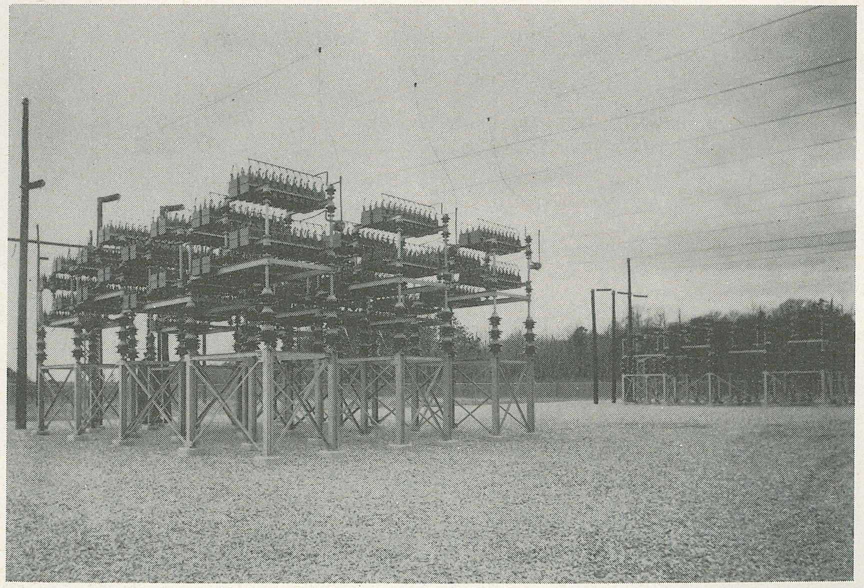

11 PARALLEL UNITS PER SERIES SECTION
15 SERIES SECTIONS PER PHASE

Fig. 4. Schematic of capacitor bank design.



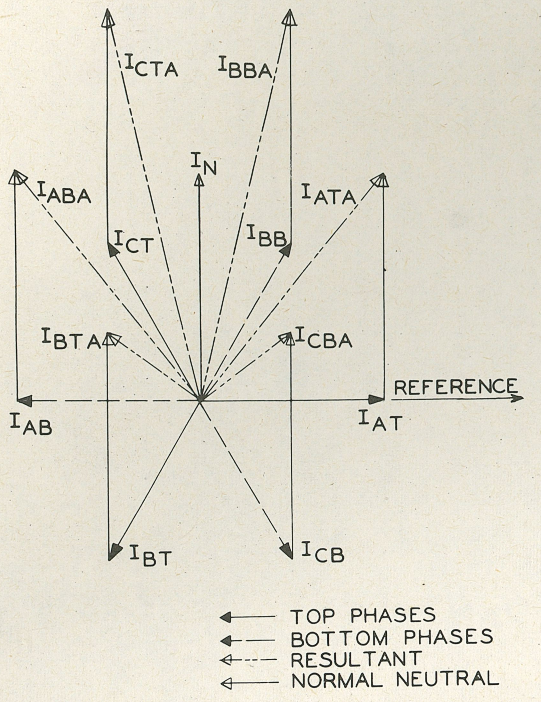


Fig. 6. Neutral current vector diagram before interchange.

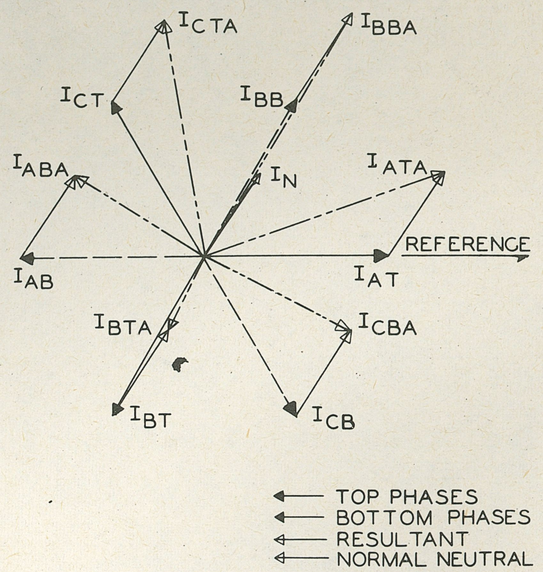


Fig. 7. Neutral current vector diagram after first interchange.

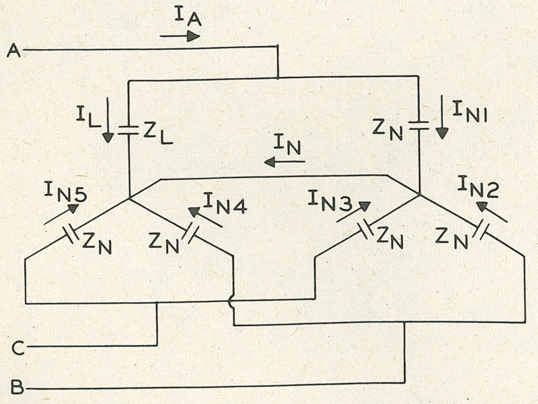


Fig. 8. Currents in double-wye connected capacitor bank.

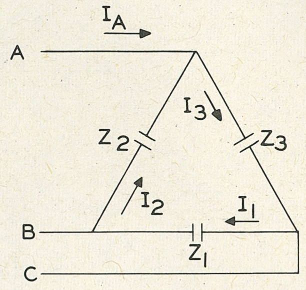


Fig. 9. Currents in equivalent delta connected capacitor bank.

Transactions Paper

(Reviewed and Accepted for Publication)

BALANCING DOUBLE-WYE HIGH VOLTAGE CAPACITOR BANKS

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A paper recommended by the AIEE Committee on Transmission and Distribution and approved by the Committee on Technical Operations for presentation at the AIEE Winter General Meeting, New York, N. Y., January 31-February 4, 1955. Manuscript submitted October 26, 1954; made available for printing December 8, 1954.

Price: 30¢ To Members
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33 West 39th Street, New York 18, N. Y.
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Paper No.
55-146

Discussion in Duplicate Due February 16, 1955.